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A New Look at the Empirical Initial-Final Mass Relation

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Abstract. We examine new methods of producing and analyzing the empirical initial-final mass relation for open cluster white dwarfs (WDs). We re-determine initial and final masses for the complete sample of published cluster WDs and then pare this sample using stringent criteria. We create an empirical initial-final mass relation by binning all WDs in individual clusters to a single point. Despite potentially significant systematics arising from this approach, we are comfortable concluding that, to within current observational constraints, the initial-final mass relation is linear, any intrinsic scatter in the relation is $\lesssim 0.05M_{\odot}$, and there is no metallicity dependence. More exploration of these issues is clearly warranted.

1. Introduction

The initial-final mass relation (IFMR) represents the integrated mass lost by a star over its entire evolution from zero-age main sequence to the white dwarf (WD) cooling sequence. As such, the IFMR can provide valuable insight into difficult issues of stellar mass loss. The IFMR is an integral part of widely-varied areas of astrophysical research, from dating the age of the Galactic disk via the WD luminosity function (e.g., Winget et al. 1987), to understanding chemical enrichment and star formation efficiencies in galaxies (e.g., Ferrario et al. 2005), to the origin and evolution of hot gas in elliptical galaxies (e.g., Mathews 1990).

The first comparison of measurements of WD masses and their progenitor masses to theoretical predictions of the IFMR was made by Weidemann (1977). With increasing numbers of open cluster WD studies and modern instrumentation, the number of published open cluster WDs has grown to ~ 50 (Ferrario et al. 2005) and is rapidly increasing (e.g., Williams & Bolte 2006, and J. Kalirai, this volume).

Despite the rapid growth in the number of observational points on the IFMR, many uncertainties remain regarding the relation. Is the relation linear or more complicated? What is the intrinsic scatter; i.e., what is the range of WD masses a main-sequence star of a given mass will produce? Is there any dependence of the IFMR on metallicity? A glance at the current empirical IFMR (see Figure 1) leads one to understand why answers to these questions have not been forthcoming – the scatter in the points is gigantic, masking any subtle trends.

In order to better understand the IFMR, including its intrinsic scatter and any metallicity dependence, a more sophisticated means of creating and analyzing the empirical IFMR is needed. We are beginning an exploration into

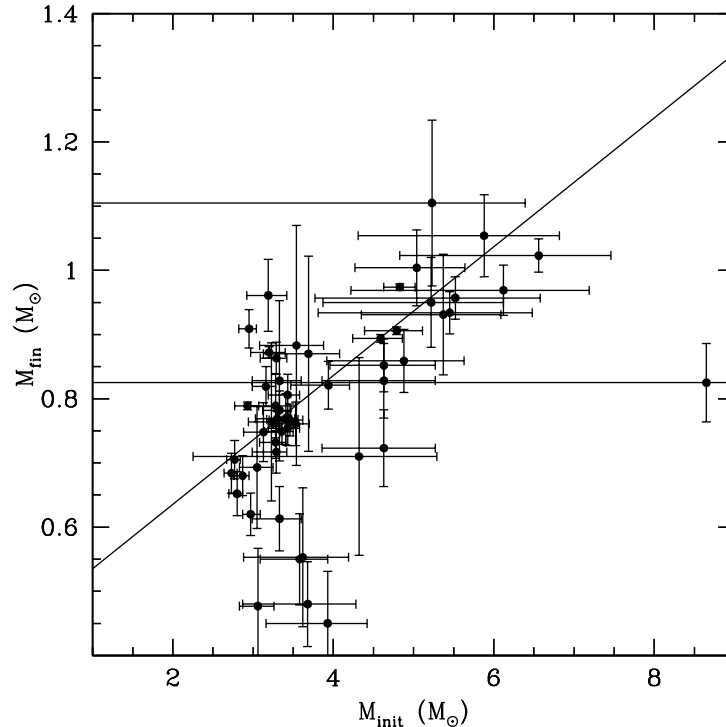


Figure 1. The empirical initial-final mass relation from Ferrario et al. (2005), including subsequent Praesepe points from work by Dobbie et al. (2006a). Error bars include observational errors and uncertainties in cluster ages. The line is the best fit model from Ferrario et al. References for individual points are given in Ferrario et al. (2005).

various means of analyzing the IFMR, and present one early attempt in these proceedings. Although the quantitative conclusions presented herein should be regarded as preliminary, we can conclude that the current WD sample is of sufficient quantity and quality to address the issues raised above. We therefore continue to explore more robust methods of analyzing the empirical IFMR.

2. Toward a Robust Empirical Initial-Final Mass Relation

Given that the current open cluster data come from a wide variety of data sets with widely varying quality and constraints, our first order of business is to put all the data on similar footing. Using published effective temperatures, surface gravities, and errors, we re-determine each open cluster WD's mass and cooling age using evolutionary models graciously provided by P. Bergeron (For description of the models, see Holberg & Bergeron 2006). Using the best-available ages for each open cluster, we subtract the WD cooling age from the cluster age to get the progenitor star age. This is converted into the progenitor's zero-age main sequence mass (the initial mass) using Padova stellar evolutionary sequences

(Girardi et al. 2002) and observed cluster metallicities (For more detailed explanation of this process, see Williams & Bolte 2006). This process leaves only the temperature and surface gravity as potential inter-sample systematic error sources.

2.1. Paring the Open Cluster White Dwarf Sample

To further reduce uncertainties, we next apply some stringent selection criteria to the WD sample. First, we reject any WDs where the uncertainty in either the open cluster age or the calculated progenitor star lifetime is $\geq 50\%$. Second, we reject any WDs with masses less than $0.5M_{\odot}$, as these are likely products of binary evolution, not the single-star evolution we wish to explore. Lastly, we reject any WDs with final mass uncertainties greater than 10% or cooling time uncertainties greater than 50% (typically WDs with low signal-to-noise observations). Finally, we only include WDs likely to be cluster members, with either proper motion determinations or apparent distance moduli within 2σ of the cluster distance modulus.

The resulting sample includes 46 WDs from eight open clusters and two binary-star systems: Sirius A/B (Liebert et al. 2005) and Procyon A/B (Liebert et al. 2006, in preparation). We note that this is not a complete sample of open cluster WDs, but as we are not making any analysis of the cluster WD mass and/or luminosity functions, this incompleteness should not make a significant difference.

2.2. A Binned Initial-Final Mass Relationship

For those clusters with multiple WDs, we now make the simplifying assumption that all WDs in a given cluster have the same progenitor mass and final mass. We determine this cluster initial mass and cluster final mass by finding the mean of the initial and final masses of individual WDs in the cluster. We define the scatter in each quantity as the standard deviation of the individual cluster WDs about the cluster means.

The binning of a cluster's WD population into a single point has one distinct advantage over previously-published IFMRs. The largest source of error in the initial mass is due to uncertainty in cluster ages. This error is systematic for WDs in a given cluster – if the cluster is older or younger, the WDs in that cluster will shift together to lower or higher initial masses (respectively) in the IFMR. For that reason it is not formally correct to add observational errors in quadrature with the cluster age errors for each individual WD, as done in the Ferrario et al. (2005). Yet errors due to cluster ages can be considered random in cluster-to-cluster comparisons. By binning all points in the cluster, the errors due to cluster ages can be represented as random errors in the IFMR.

We note that binning is not a formally correct tactic – we expect individual cluster WDs to have a range of initial masses and final masses. However, for all clusters except M35 and Praesepe, we note that the distribution of cluster WDs about the cluster means are consistent with a Gaussian distribution. Still, the assumption that each cluster has a single initial and final mass needs to be relaxed in further work on this topic.

This binned initial-final mass relation is shown in Figure 2. Comparison with Figure 1 shows that the relationship appears much tighter. Also shown in

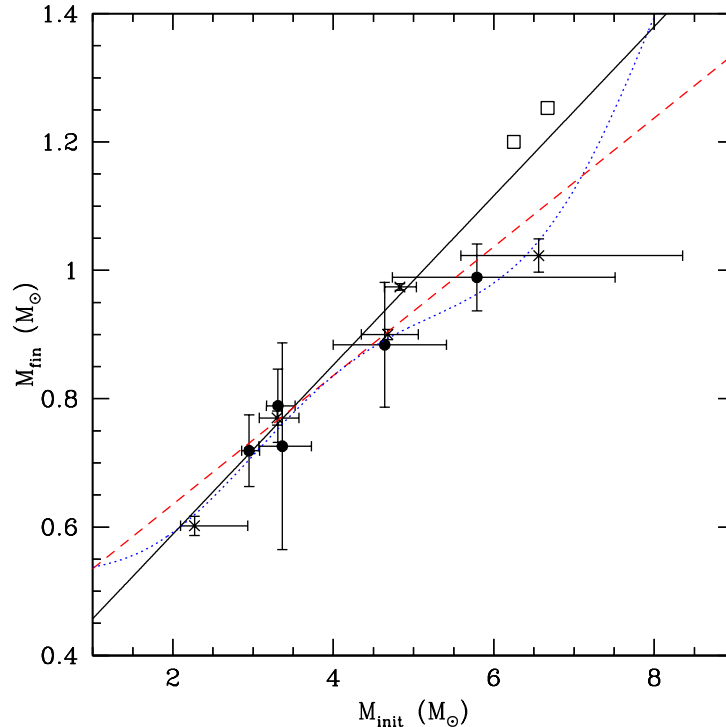


Figure 2. The binned initial-final mass relation. Filled circles are binned points from open clusters with four or more WDs; crosses are from clusters or binary systems with three or fewer WDs. The solid line is a least-squares linear fit to these points. The dashed line is the linear fit from Ferrario et al. (2005); the dotted line is the inversion of the field WD mass distribution presented in that work. Open squares, which were *not* included in the fits, are from other work presented at this conference; namely, Dobbie et al.’s (2006b) points for GD 50 and PG 0136+251. The agreement between these points and the extrapolation of the linear fit is encouraging.

the Figure are the linear relation from Ferrario et al. (2005) (dashed line) and their relation obtained from inverting the field WD mass function (dotted line). Neither line is a poor fit, and the inflections at high masses in the inverted fit mirror potential inflections in the empirical relation. We use least-squares fitting to obtain our own linear fit to the binned IFMR:

$$M_f = (0.132 \pm 0.017)M_i + 0.33 \pm 0.07.$$

This line is shown (solid) in Figure 2.

3. Discussion

Using this binned IFMR, we now explore some of the issues raised in the introduction.

Table 1. Stated Errors and Observed Scatter in Open Cluster Final Masses

Cluster	M_f (M_\odot)	Stated Error (M_\odot)	Measured Scatter (M_\odot)
Hyades	2.95	0.033	0.056
Praesepe	3.31	0.030	0.057
NGC 2099	3.36	0.095	0.161
M35	4.64	0.060	0.097

Is the IFMR linear or more complicated? — The χ^2 value of the linear fit to the binned IFMR, $\chi^2 = 2.74$ with 2 degrees of freedom, is an acceptable fit, though qualitatively it appears that some curvature in the high-mass end of the IFMR may be warranted. Since the linear fit was calculated, new data have been published for the high-mass WDs GD 50 and PG 0136+251, assuming both are escaped members of the Pleiades (Dobbie et al. 2006b). These points are shown in Figure 2 as open squares, and, despite the large error bars (not shown), these points lie remarkably close to the linear binned IFMR. We also note that points presented by J. Kalirai at this conference lie close to extrapolation of this line at the low-mass end of the relation. We therefore conclude that there is no strong evidence that the IFMR is non-linear at the current levels of observational precision.

What is the intrinsic scatter in the IFMR? — We can estimate the internal scatter in the IFMR based on four clusters with more than 5 WDs: M35, NGC 2099, Praesepe, and the Hyades. We compare the stated observational errors with the measured scatter for each cluster in the binned IFMR (see Table 1). In all four cases, the measured scatter is larger than the stated errors, with an additional $0.05M_\odot$ of scatter required. The additional scatter may be due to intrinsic scatter in the IFMR, but it could also be due to an understatement of the observational errors or to systematic errors caused by the assumption that all WDs in a given cluster have the same initial mass and the same final mass. As both of these will tend to increase the intrinsic scatter, however, we can state with reasonable confidence that the internal scatter of the IFMR is $\lesssim 0.05M_\odot$.

Is the IFMR metallicity-dependent? — Given that many mass-loss mechanisms in evolved stars rely on metals and thus are metallicity-dependent, it is reasonable to suspect that the IFMR is metallicity dependent. Kalirai et al. (2005), using data from NGC 2099, claim to find some indication that the IFMR may be dependent on metallicity. We briefly explore this by comparing the binned points for three clusters of nearly-identical ages: the Hyades, with $M_i = 2.95 \pm 0.1$, $M_f = 0.72 \pm 0.06$, and $[\text{Fe}/\text{H}] = 0.14$ (Perryman et al. 1998); Praesepe, with $M_i = 3.31 \pm 0.15$, $M_f = 0.79 \pm 0.06$, and $[\text{Fe}/\text{H}] = 0.14$ (Claver et al. 2001); and NGC 2099, with $M_i = 3.4 \pm 0.3$, $M_f = 0.73 \pm 0.16$, and $[\text{Fe}/\text{H}] \approx -0.24$ (Kalirai et al. 2005). Despite a difference in metallicity of ≈ 0.4 dex, there are no significant differences in M_f between these three points. Therefore, any metallicity dependence of the IFMR for $M_i \approx 3M_\odot$ must be smaller than $\Delta M_f \approx 0.05M_\odot$.

We again acknowledge that the quantitative conclusions above may be affected quite markedly by our simplifying assumption that each cluster can be

represented by a single data point in the empirical IFMR. However, we feel that the data are still of sufficient quality to make a few general conclusions. Specifically, we conclude that the IFMR appears to be linear within current observational limits over the currently-observed range of initial masses. We also conclude that intrinsic scatter in the relation at a given initial mass is on the order of or smaller than the observational errors and that there is no compelling evidence for a metallicity dependence in the IFMR to within the observational errors, at least for initial masses $\sim 3M_{\odot}$. Further work on understanding the empirical IFMR and teasing out more quantitative answers clearly remains.

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